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PRELIMINARY ESTIMATES OF GALACTIC COSMIC RAY SHIELDING REQUIREMENTS
FOR MANNED INTERPLANETARY MISSIONS

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ABSTRACT

Estimates of radiation risk to the blood forming organs from galactic cosmic rays are presented for manned interplanetary missions. The calculations use the Naval Research Laboratory cosmic ray spectrum model as input into the Langley Research Center galactic cosmic ray transport code. This transport code, which transports both heavy ions and nucleons, can be used with any number of layers of target material, consisting of up to five different arbitrary constituents per layer. Calculated galactic cosmic ray doses and dose equivalents behind various thicknesses of aluminum and water shielding are presented for solar maximum and solar minimum periods. Estimates of risk to the blood forming organs are made using 5-cm depth dose/dose equivalent values for water. These results indicate that at least 5 g/cm^2 (5 cm) of water or 6.5 g/cm^2 (2.4 cm) of aluminum shielding is required to reduce the annual exposure below the currently recommended limit of 50 rem. Because of the large uncertainties in fragmentation parameters, and the input cosmic ray spectrum, these exposure estimates may be uncertain by as much as 70 percent. Therefore, more detailed analyses with improved inputs could indicate the need for additional shielding.

INTRODUCTION

As the twentieth century draws to a close, there is an ever-increasing interest in manned interplanetary travel. In particular, current attention is focussed upon manned missions to the Earth's moon and to the planet Mars and its satellites. A major concern to interplanetary mission planners is exposure of the crew to highly penetrating and damaging space radiations. The two major sources of these radiations are solar particle events (SPE) and galactic cosmic rays (GCR). Estimates of radiation exposures to the blood forming organs (BFO) from energetic solar proton events (flares) are presented in reference 1. In addition, preliminary calculations of GCR exposures in aluminum were presented previously (ref. 2). These latter estimates were of limited usefulness, however, because of the restriction to non-hydrogenous targets imposed by the missing nucleon-hydrogen cross section data bases in the transport code. To rectify that limitation in the present code, the HZE (high-energy heavy ion) component of the previous GCR transport code (ref. 3) has been coupled to a modified version of the Langley Research Center nucleon transport code BRYNTRN (ref. 4). This coupling of the two deterministic transport codes produces a single complete code for use in GCR shielding and dosimetry studies. This code, however, is considered to be interim in that it does not treat meson contributions, neglects target fragments produced by propagating protons and heavy ions, uses accurate but somewhat simplified input cross sections, and has not been optimized for computational efficiency. The neglect of target fragment contributions from the incident GCR protons has been corrected for in the

calculations by computing the contribution using BRYNTRN (ref. 4) and adding the results to the proton dose/dose equivalent predictions presented herein. Nevertheless, the present interim computer code is useful for initial exposure and shield requirement estimates.

In this report, preliminary estimates of integral fluxes (particles/cm^2/year), doses (rad/year), and dose equivalents (rem/year) in tissue, behind various thicknesses of aluminum and water shielding, are presented according to particle composition (protons, neutrons, alphas, and HZE) and as LET (linear energy transfer) spectra. The calculations, which include both solar maximum and solar minimum periods, use as the input spectrum the analytical model of the GCR environment promulgated by the Naval Research Laboratory (ref. 5).

CALCULATIONAL METHODS

The incident galactic cosmic ray spectrum (ref. 5) for free space is propagated through the target material using the accurate analytical/numerical solutions to the transport equation described in references 3 and 4. These highly accurate solution methods have been verified (to within 2-percent accuracy) by comparison with an exact, analytical benchmark solution to the ion transport equation (refs. 6 and 7).

These transport calculations include:

a. ICRP-26 quality factors (ref. 8).

b. Dose contributions from propagating neutrons, protons, alpha particles, and heavy ions (HZE particles).

c. Dose contributions resulting from target nuclear fragments produced by incident neutrons and protons.

d. Dose contributions due to nuclear recoil in tissue.

Major shortcomings of the calculations are:

a. Except for tissue targets, mass number 2 and 3 fragment contributions are neglected.

b. Target fragmentation contributions from HZE particles are neglected (although they are included for nucleons).

c. It is presently assumed that all secondary particles are produced with a velocity equal to that of the incident particle. For neutrons produced in HZE particle fragmentations, this is conservative.

d. A quality factor of 20 is assigned to all multiply charged target fragments. To improve this approximation, one needs to calculate target fragment spectra correctly.

e. Meson contributions to the propagating radiation fields are neglected.

f. Nucleus-nucleus cross sections are not fully energy-dependent (nucleon-nucleus cross sections are fully energy-dependent).

RESULTS

Figure 1 displays dose equivalent (in units of rem/year) as a function of water shield thickness (in units of areal density, g/cm^2, or thickness, cm). Curves are displayed for solar minimum and solar maximum periods. The numerical values used in the figure are listed in Table I. Also listed in this table are values for the absorbed dose (in rad/year) as a function of water shield thickness. The actual compositions of the calculated radiation fields are displayed in Tables II-IV where values for dose equivalent, dose, and particle flux are listed by particle type (neutrons, protons, alphas, and HZE) as a function of water and shield thickness.

The target fragment dose/dose equivalent contributions for protons, computed using BRYNTRN (ref. 4), are displayed separately in these tables.

Because many damage mechanisms in biological systems, electronic components, and structural materials may be LET-dependent, Tables V-VII display values of particle flux, dose, and dose equivalent as a function of LET (in MeV-cm^2/g) and water shield thickness. Values are listed for both solar minimum and solar maximum periods. All dose and flux quantities are integral values. Comparable tables for aluminum shields, listed in reference 1, will not be repeated herein. The calculated LET spectra in Tables V-VII do not include target fragment contributions.

From Table I (or Figure 1), estimates of the thicknesses of water shielding required to protect astronauts from GCR particles can be obtained. At present there are no recommended exposure limits for exploratory class missions. Therefore, we will utilize the currently proposed annual limits for Space Station Freedom (ref. 9). These are 300 rem to the eye (0.01-cm depth), 200 rem to the skin (0.3-cm depth), and 50 rem to the blood forming organs-BFO (5-cm depth). Clearly, from Table I, none of these limits are exceeded during periods of solar maximum activity, as the unshielded (0-cm depth) dose equivalent is estimated to be less than 50 rem. Similarly, during solar minimum periods, the estimated unshielded dose equivalent of 120.5 rem does not exceed either the skin or the eye exposure limits. The dose equivalent at 5-cm depth, which yields an estimate of the unshielded BFO

exposure, is 64-rem, which exceeds the 50-rem limit by 28 percent. To reduce this estimated exposure below 50 rem requires approximately 5 g/cm^2 (5 cm) of water shielding.

For comparison purposes, calculations of BFO exposures behind various thicknesses (up to 10 g/cm^2) of aluminum shielding were made. The results are presented in Tables VIII and IX. For aluminum, 6.5 g/cm^2 (2.4 cm) of shielding thickness is required to reduce the BFO dose equivalent below the 50-rem annual limit. Comparing Tables I and VIII, it is apparent that the added shielding effectiveness of water is not significant for thin shields (< 5 g/cm^2) but can be significant for thicker shields. These results demonstrate that a major source of BFO shielding is the body self-shielding of the astronauts themselves.

The preliminary nature of these calculations cannot be overemphasized. From Figure 1 it is apparent that the dose equivalent is a slowly decreasing function of shield thickness. This is a result of secondary particle production processes whereby the heavier GCR nuclei are broken up into nucleons and lighter nuclear fragments by nuclear and Coulombic interactions with the shield material. This slow decrease in dose equivalent with increasing shield thickness means that relatively small uncertainties in predicted doses may yield large uncertainties in estimated shield thicknesses. For example, if the actual dose equivalent during solar minimum is 20-percent larger than the predictions in Table I, the water shield thickness required to reduce the estimated BFO dose equivalent below the 50-rem limit increases from 5 g/cm^2 to 16 g/cm^2 — which means a tripling of the required

shield mass. To estimate the actual uncertainties in the results presented herein, we note that previous studies of the uncertainties introduced into transport calculations (ref. 10) through the use of energy-independent nucleus-nucleus absorption cross sections and fragmentation parameters suggest that the predicted HZE doses may be underestimated by as much as 10-20 percent, depending upon the accuracy of the fragmentation model used. In addition, the overall uncertainty in the input GCR spectrum may be as large as 20-50 percent (ref. 5). Therefore, the total uncertainty in our dose/dose equivalent estimates may be as large as 30-70 percent. If the predicted doses/dose equivalents are increased by 50 percent to account for these uncertainties, then the water shield thickness required to limit BFO exposures to 50 rem/year increases from 5 g/cm^2 to 25 g/cm^2. Clearly, the uncertainties in the actual GCR environmental model and in the input nuclear fragmentation models need to be resolved through additional theoretical and experimental research. Finally, we note that radiation exposure is cumulative and therefore requires consideration of contributions from all sources including on-board nuclear power sources, solar particle events, and galactic cosmic rays. Exposure to on-board sources will reduce the allowed exposures from solar flares and cosmic rays and thereby increase required shield thicknesses necessary to stay below the approved exposure limits.

CONCLUDING REMARKS

Preliminary estimates of radiation exposures resulting from galactic cosmic rays are presented for interplanetary missions. Particle flux, dose, and dose

equivalent values are presented, for both solar maximum and minimum periods, as a function of water and aluminum shield thickness, and as a function of linear energy transfer. The main contributions to the radiation doses arise from high-energy heavy ion (HZE) particles. As the incident radiations attenuate in the shield material, there is a significant buildup of secondary particles resulting from nuclear fragmentation and Coulomb dissociation processes. A substantial fraction of these secondaries are energetic protons and neutrons. During solar minimum periods, at least 5 g/cm^2 of water shielding, or 6.5 g/cm^2 of aluminum shielding will be needed to keep the estimated risk to the blood forming organs below the current annual Space Station Freedom limit of 50 rem/year. Significant uncertainties in the input cosmic ray spectra, and in the input nuclear fragmentation cross sections, could significantly alter these estimates, however, by requiring substantial quantities of additional shielding to compensate for their effects.

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Table I - Galactic Cosmic Ray Dose (rad/yr) and Dose Equivalent (rem/yr) in Tissue
as a Function of Water Shield Thickness

Thickness (cm or g/cm^2)	Solar Maximum Period		Solar Minimum Period	
	Dose (rad/yr)	Dose Equivalent (rem/yr)	Dose (rad/yr)	Dose Equivalent (rem/yr)
0	6.36	45.1	17.43	120.5
1	5.45	29.1	14.98	83.3
2	5.49	28.1	14.84	77.5
3	5.52	27.0	14.69	72.2
4	5.54	26.0	14.55	67.7
5	5.55	25.0	14.44	63.7
6	5.56	24.2	14.32	60.3
7	5.58	23.4	14.23	57.2
8	5.59	22.6	14.13	54.5
9	5.60	21.9	14.05	52.1
10	5.61	21.2	13.98	49.9
11	5.62	20.6	13.91	48.0
12	5.63	20.1	13.86	46.2
13	5.64	19.6	13.80	44.6
14	5.64	19.1	13.74	43.2
15	5.65	18.7	13.70	41.9
16	5.66	18.3	13.65	40.7
17	5.67	17.8	13.61	39.7
18	5.68	17.5	13.57	38.6
19	5.69	17.2	13.52	37.8
20	5.69	16.9	13.49	36.9
25	5.71	15.6	13.32	33.6
30	5.73	14.7	13.14	31.2

Table II - Galactic Cosmic Ray Dose Equivalent (rem/yr) in Tissue as a Function of Particle Type and Water Shield Thickness

Thickness (cm or g/cm^2)	Neutrons	Protons	Target Fragments	Alphas	HZE
SOLAR MINIMUM PERIOD					
0	0	9.72	0	6.95	102.54
5	1.78	8.11	5.78	2.92	45.07
10	3.26	9.28	5.62	2.40	29.26
15	4.47	10.08	5.43	1.98	19.88
20	5.47	10.64	5.23	1.63	13.89
25	6.29	11.01	5.02	1.34	9.89
30	6.95	11.26	4.80	1.11	7.14
SOLAR MAXIMUM PERIOD					
0	0	4.06	0	2.39	38.07
5	0.83	3.10	2.70	0.92	17.48
10	1.53	3.64	2.64	0.78	12.62
15	2.12	4.05	2.57	0.67	9.23
20	2.63	4.36	2.49	0.57	6.82
25	3.05	4.60	2.41	0.48	5.07
30	3.40	4.79	2.34	0.41	3.80

Table III - Galactic Cosmic Ray Dose (rad/yr) in Tissue as a Function of Particle Type and Water Shield Thickness

Thickness (cm or g/cm²)	Neutrons	Protons	Target Fragments	Alphas	HZE
SOLAR MINIMUM PERIOD					
0	0	6.21	0	3.02	7.82
5	0.39	7.18	0.29	2.30	4.25
10	0.71	8.07	0.28	1.91	3.00
15	0.98	8.67	0.27	1.58	2.19
20	1.19	9.08	0.26	1.31	1.63
25	1.37	9.36	0.26	1.09	1.23
30	1.51	9.52	0.25	0.91	0.94
SOLAR MAXIMUM PERIOD					
0	0	2.33	0	1.05	2.95
5	0.18	2.71	0.13	0.80	1.72
10	0.34	3.13	0.13	0.69	1.32
15	0.47	3.44	0.13	0.59	1.02
20	0.58	3.68	0.12	0.50	0.80
25	0.68	3.86	0.12	0.43	0.63
30	0.75	4.00	0.12	0.36	0.49

Table IV - Galactic Cosmic Ray Flux (particles/cm^2/yr)
as a Function of Particle Type and Water Shield Thickness

Thickness (cm or g/cm^2)	Neutrons	Protons	Alphas	HZE
		SOLAR MINIMUM PERIOD		
0	0	1.29 E + 08	1.24 E + 07	1.39 E + 06
5	2.33 E + 07	1.38 E + 08	1.04 E + 07	1.10 E + 06
10	4.27 E + 07	1.43 E + 08	8.79 E + 06	8.86 E + 05
15	5.88 E + 07	1.46 E + 08	7.39 E + 06	7.23 E + 05
20	7.21 E + 07	1.47 E + 08	6.22 E + 06	5.94 E + 05
25	8.30 E + 07	1.47 E + 08	5.24 E + 06	4.91 E + 05
30	9.19 E + 07	1.46 E + 08	4.42 E + 06	4.06 E + 05
		SOLAR MAXIMUM PERIOD		
0	0	5.12 E + 07	5.13 E + 06	5.73 E + 05
5	1.05 E + 07	5.55 E + 07	4.39 E + 06	4.83 E + 05
10	1.96 E + 07	5.85 E + 07	3.77 E + 06	4.09 E + 05
15	2.73 E + 07	6.06 E + 07	3.23 E + 06	3.47 E + 05
20	3.39 E + 07	6.21 E + 07	2.77 E + 06	2.94 E + 05
25	3.95 E + 07	6.31 E + 07	2.37 E + 06	2.50 E + 05
30	4.41 E + 07	6.37 E + 07	2.03 E + 06	2.12 E + 05

Table V - Flux (particles/cm²/yr) vs. LET in Water

LET (MeV-cm²/g)	Thickness in g/cm² or cm						
	0	5	10	15	20	25	30
			SOLAR MINIMUM PERIOD				
1.08E+00	1.43E+08	1.73E+08	1.95E+08	2.13E+08	2.26E+08	2.36E+08	2.43E+08
5.03E+00	1.86E+07	4.61E+07	6.79E+07	8.54E+07	9.96E+07	1.11E+08	1.20E+08
2.35E+01	3.03E+06	2.62E+07	4.55E+07	6.15E+07	7.47E+07	8.55E+07	9.44E+07
1.09E+02	1.07E+06	2.40E+07	4.33E+07	5.93E+07	7.25E+07	8.33E+07	9.22E+07
5.10E+02	1.91E+05	3.36E+05	5.55E+05	7.61E+05	9.32E+05	1.07E+06	1.18E+06
2.38E+03	1.63E+04	3.95E+04	7.47E+04	1.08E+05	1.35E+05	1.57E+05	1.75E+05
1.11E+04	1.77E+03	3.35E+04	7.14E+04	1.06E+05	1.34E+05	1.57E+05	1.74E+05
5.16E+04	7.33E+01	3.33E+04	7.12E+04	1.06E+05	1.34E+05	1.57E+05	6.74E+05
			SOLAR MAXIMUM PERIOD				
1.08E+00	5.69E+07	7.09E+07	8.23E+07	9.15E+07	9.91E+07	1.05E+08	1.10E+08
5.03E+00	6.60E+06	1.89E+07	2.91E+07	3.76E+07	4.48E+07	5.08E+07	5.58E+07
2.35E+01	1.02E+06	1.16E+07	2.06E+07	2.84E+07	3.50E+07	4.05E+07	4.52E+07
1.09E+02	4.13E+05	1.08E+07	1.98E+07	2.75E+07	3.41E+07	3.96E+07	4.43E+07
5.10E+02	6.72E+04	1.40E+05	2.42E+05	3.37E+05	4.19E+05	4.88E+05	5.43E+05
2.38E+03	4.50E+03	1.68E+04	3.35E+04	4.92E+04	6.27E+04	7.38E+04	8.28E+04
1.11E+04	8.48E+02	1.51E+04	3.24E+04	4.84E+04	6.21E+04	7.34E+04	8.25E+04
5.16E+04	7.51E+01	1.50E+04	3.23E+04	4.84E+04	6.21E+04	7.33E+04	8.24E+04

Table VI - Dose (rad/yr) vs. LET in Water

LET (MeV-cm^2/g)	Thickness in g/cm^2 or cm						
	0	5	10	15	20	25	30
	SOLAR MINIMUM PERIOD						
1.08E+00	1.71E+01	1.41E+01	1.37E+01	1.34E+01	1.32E+01	1.31E+01	1.29E+01
5.03E+00	1.22E+01	9.07E+00	8.53E+00	8.21E+00	8.00E+00	7.86E+00	7.75E+00
2.35E+01	9.65E+00	5.92E+00	5.09E+00	4.60E+00	4.29E+00	4.09E+00	3.96E+00
1.09E+02	8.12E+00	4.40E+00	3.54E+00	3.07E+00	2.79E+00	2.63E+00	2.53E+00
5.10E+02	5.07E+00	1.97E+00	1.26E+00	8.43E-01	5.85E-01	4.18E-01	3.05E-01
2.38E+03	2.22E+00	4.00E-01	2.14E-01	1.24E-01	7.62E-02	4.84E-02	3.17E-02
1.11E+04	1.20E+00	4.72E-02	2.47E-02	1.43E-02	8.85E-03	5.77E-03	3.93E-03
5.16E+04	7.11E-04	6.74E-04	6.72E-04	6.82E-04	6.94E-04	7.02E-04	7.05E-04
	SOLAR MAXIMUM PERIOD						
1.08E+00	6.36E+00	5.42E+00	5.48E+00	5.52E+00	5.56E+00	5.59E+00	5.61E+00
5.03E+00	4.48E+00	3.45E+00	3.43E+00	3.42E+00	3.42E+00	3.43E+00	3.44E+00
2.35E+01	3.59E+00	2.30E+00	2.13E+00	2.03E+00	1.96E+00	1.91E+00	1.88E+00
1.09E+02	3.05E+00	1.74E+00	1.54E+00	1.42E+00	1.34E+00	1.29E+00	1.26E+00
5.10E+02	1.87E+00	7.50E-01	5.39E-01	3.92E-01	2.89E-01	2.16E-01	1.63E-01
2.38E+03	8.31E-01	1.05E-01	6.70E-02	4.39E-02	2.95E-02	2.02E-02	1.40E-02
1.11E+04	5.65E-01	1.25E-02	8.18E-03	5.54E-03	3.89E-03	2.83E-03	2.14E-03
5.16E+04	7.36E-04	6.83E-04	6.67E-04	6.66E-04	6.68E-04	6.69E-04	6.67E-04

Table VII - Dose Equivalent (rem/yr) vs. LET in Water

LET (MeV-cm²/g)	Thickness in g/cm² or cm						
	0	5	10	15	20	25	30
SOLAR MINIMUM PERIOD							
1.08E+00	1.21E+02	5.79E+01	4.43E+01	3.65E+01	3.17E+01	2.86E+01	2.65E+01
5.03E+00	1.15E+02	5.28E+01	3.91E+01	3.12E+01	2.65E+01	2.34E+01	2.14E+01
2.35E+01	1.13E+02	4.97E+01	3.56E+01	2.76E+01	2.27E+01	1.96E+01	1.76E+01
1.09E+02	1.10E+02	4.72E+01	3.32E+01	2.53E+01	2.05E+01	1.74E+01	1.55E+01
5.10E+02	9.13E+01	3.36E+01	2.10E+01	1.38E+01	9.39E+00	6.57E+00	4.71E+00
2.38E+03	4.43E+01	7.98E+00	4.27E+00	2.47E+00	1.51E+00	9.55E-01	6.21E-01
1.11E+04	2.40E+01	9.37E-01	4.87E-01	2.77E-01	1.67E-01	1.05E-01	6.79E-02
5.16E+04	1.25E-02	9.10E-03	7.08E-03	5.79E-03	4.96E-03	4.40E-03	4.03E-03
SOLAR MAXIMUM PERIOD							
1.08E+00	4.51E+01	2.23E+01	1.86E+01	1.61E+01	1.44E+01	1.32E+01	1.24E+01
5.03E+00	4.31E+01	2.04E+01	1.65E+01	1.40E+01	1.23E+01	1.11E+01	1.02E+01
2.35E+01	4.21E+01	1.92E+01	1.52E+01	1.26E+01	1.08E+01	9.54E+00	8.68E+00
1.09E+02	4.10E+01	1.83E+01	1.43E+01	1.16E+01	9.82E+00	8.59E+00	7.74E+00
5.10E+02	3.40E+01	1.28E+01	8.98E+00	6.40E+00	4.63E+00	3.38E+00	2.50E+00
2.38E+03	1.66E+01	2.08E+00	1.33E+00	8.65E-01	5.75E-01	3.89E-01	2.67E-01
1.11E+04	1.13E+01	2.43E-01	1.55E-01	1.01E-01	6.73E-02	4.57E-02	3.15E-02
5.16E+04	1.29E-02	9.14E-03	6.73E-03	5.14E-03	4.05E-03	3.31E-03	2.80E-03

Table VIII - Galactic Cosmic Ray 5-cm Depth Dose Equivalent (rem/yr) in Tissue as a Function of Particle Type and Aluminum Shield Thickness

Thickness[a] g/cm²	Neutrons	Protons	Target Fragments	Alphas	HZE	Total Dose Equivalent
			SOLAR MINIMUM PERIOD			
1	2.66	8.25	5.77	2.67	39.64	59.00
2	3.05	8.48	5.76	2.60	37.00	56.90
3	3.43	8.69	5.75	2.53	34.60	55.01
4	3.80	8.89	5.74	2.46	32.42	53.31
5	4.16	9.07	5.71	2.40	30.41	51.76
10	5.85	9.79	5.61	2.09	22.56	45.91
			SOLAR MAXIMUM PERIOD			
1	1.24	3.18	2.70	0.86	15.13	23.11
2	1.44	3.29	2.70	0.84	14.44	22.71
3	1.63	3.40	2.69	0.83	13.78	22.33
4	1.82	3.50	2.69	0.81	13.15	21.98
5	2.01	3.60	2.68	0.79	12.56	21.64
10	2.91	4.00	2.66	0.71	10.03	18.31

[a] 1 g/cm² of aluminum is equivalent to 0.37 cm thickness

**Table IX - Galactic Cosmic Ray 5-cm Depth Dose (rad/yr) in Tissue
as a Function of Particle Type and Aluminum Shield Thickness**

Thickness[a] g/cm^2	Neutrons	Protons	Target Fragments	Alphas	HZE	Total Dose
			SOLAR MINIMUM PERIOD			
1	0.45	7.55	0.29	2.26	4.20	14.47
2	0.50	7.74	0.29	2.20	3.97	14.42
3	0.56	7.91	0.29	2.15	3.76	14.38
4	0.62	8.06	0.29	2.09	3.56	14.34
5	0.67	8.20	0.28	2.04	3.38	14.30
10	0.92	8.77	0.28	1.78	2.64	14.11
			SOLAR MAXIMUM PERIOD			
1	0.21	2.88	0.13	0.79	1.68	5.70
2	0.24	2.98	0.13	0.77	1.62	5.74
3	0.27	3.06	0.13	0.75	1.56	5.78
4	0.30	3.14	0.13	0.74	1.50	5.81
5	0.33	3.22	0.13	0.72	1.44	5.85
10	0.46	3.54	0.13	0.65	1.19	5.96

[a]1 g/cm^2 of aluminum is equivalent to 0.37 cm thickness
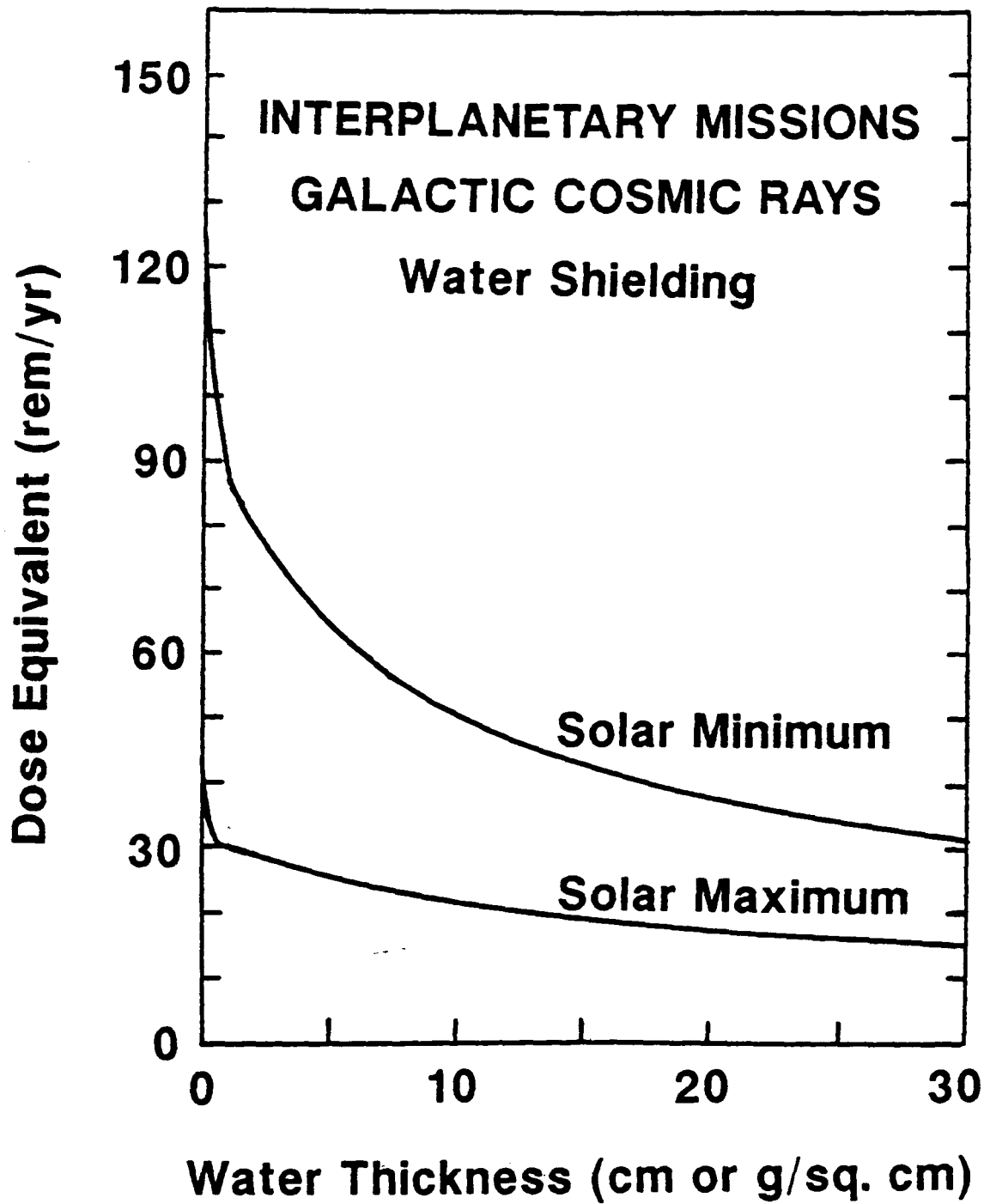
Figure 1. - Dose equivalent in water, as a function of water shield thickness, resulting from galactic cosmic rays.

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15. Supplementary Notes

16. Abstract

Estimates of radiation risk to the blood forming organs from galactic cosmic rays are presented for manned interplanetary missions. The calculations use the Naval Research Laboratory cosmic ray spectrum model as input into the Langley Research Center galactic cosmic ray transport code. This transport code, which transports both heavy ions and nucleons, can be used with any number of layers of target material, consisting of up to five different constituents per layer. Calculated galactic cosmic ray doses and dose equivalents behind various thicknesses of aluminum and water shielding are presented for solar maximum and solar minimum periods. Estimates of risk to the blood forming organs are made using 5-cm depth dose/dose equivalent values for water. These results indicate that at least 5 g/cm^2 (5 cm) of water or 6.5 g/cm^2 (2.4 cm) of aluminum shielding is required to reduce the annual exposure below the currently recommended limit of 50 rem. Because of the large uncertainties in fragmentation parameters, and the input cosmic ray spectrum, these exposure estimates may be uncertain by as much as 70 percent. Therefore, more detailed analyses with improved inputs could indicate the need for additional shielding.

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